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# A CMOS Visual Sensing System for Welding Control and Information Acquirement in SMAW Process

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**Abstract**

A sequential research work on visual information of manual arc welding pool dynamics are presented in this paper. An optical inspection system, for monitoring the shielded manual arc welding (SMAW) process is described. The system consisted of a vision sensor that consisted of a Complementary Metal Oxide Semiconductor (CMOS) camera and lenses, image processing algorithms, and a computer controller. During welding, an image of the weld pool and its vicinity was captured when basic current of welding power. Experimental results showed that the temperature signal varies greatly in the case of instabilities of the weld pool that cause weld defects. The visual information acquirement methods are focused in computer vision sensing, image processing and characteristic extraction of the weld pool surface from the single-item pool images by particular algorithms control strategies are developed to control welding pool dynamics during SMAW.


*Keywords: Visual; Arc；　Weld; CMOS*

## 1. Introduction

Manual welding is still being widely applied in the field of welding. It is very necessary to detect the status of the welding process in control of the welding process. A welding sensor can detect the status of the welding process and supply characteristic information of the welding process. A welding sensor is the basis of welding modelling and controlling, so the welding sensing technology is the key to realizing automatic and intelligent welding [1].

An experienced welder can determine whether the welding processing is right or not, and can adjust the welding parameters by observing arc behaviour, the shape of the weld pool, and the metal transfer. During the process, 80% of the information is acquired visually. Researching for the visual sensing is important for intelligent automatic welding. A visual sensor has the following advantages: it can provide

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abundant information about the weld pool, arc behaviour, joint type; well dynamic response; without contact with the welding circuit or the work piece; and it can be controlled from arc glare and heat-flash. A visual sensor can be used to extract dynamic information about the welding process and to realize seam-tracking for all kinds of grooves, it is the most promising welding sensor. At present, visual sensors have been widely utilized in seam-tracking, observation of weld pool behaviour, observation of metal transfer, and observation of arc behaviour [2].

A CMOS image sensor is a device that converts an optical image into electrical signals using MOS (metal oxide semiconductor) transistors. The CMOS image sensor sequentially detects electrical signals of each unit pixel in a switching mode to realize an image through formation of a photodiode and a MOS transistor within a unit pixel. The primary building block of an image formed by a CMOS image sensor is a pixel. The signal produced by each pixel is generally extremely small, but is related to the amount of incident light photons. In a CMOS image sensor, the active elements of a pixel cell perform the necessary functions of photon to charge conversion, accumulation of image charge, transfer of charge to the sensing node accompanied by charge amplification, resetting the sensing node to a known state before the transfer of charge to it, selection of a pixel for readout, and output and amplification of a signal representing pixel charge from the sensing node. The primary advantages of CMOS imagers are their relatively low cost generally resulting from the use of standard, high-volume CMOS processes and their ability to be integrated with native CMOS electronics for control and image processing.

According to imaging principles, in an ideal situation, the imaging process is very simple, and the gray level of the image only depends on the angle between the incident ray and surface normal, the reflectance characteristic of the object's surface, and the incident light intensity. However, welding process sensing does not offer ideal imaging conditions. The gray level of the image is relative to the shape and position of the illumination, the object surface shape, the surface reflectance characteristics, the position and parameters of camera, etc. A passive visual sensing system and the inner setting of the camera from the point of view of the light intensity are analyzed in this paper, and the influencing factors are formulated.

## 2. The principle of passive visual sensing

The function of a visual sensor in the control of the welding process is to transform an optical image into a video signal. Characteristic information about the welding process is acquired, and a control signal is sent to realize close-loop control of the welding process.Intense arc light accompanies the welding process. The arc spectrum is very complex, consisting of a continuous component from light emitted as a result of electronic transitions near the weld pool surface, as well as a spectral peak from light emitted by shielded gases remote from weld pool surface. The total intensity of the arc light is several times that of the continuous spectrum alone [3].

The object is to select a window from the arc spectrum where it is mainly continuous, and to adjust the arc light intensity to a suitable level by a complex filter system. The visual sensing system can be used to observe the shape and size of the weld pool, the arc position, and the offset between the centre of the weld pool and the seam. The arc, the weld pool, and the seam can concurrently form an image in the range of visible light [4].

A CMOS camera can automatic reduce the incident light intensity. According to the relationship of welding current and arc light intensity, the popular method is to combine capturing the image at a low current with using a complex filter. The arc light is weaker during the base current; also, the arc light intensity can be reduced by a neutral-density filter and narrow-band filter so that the arc disturbance is reduced and the detailed information of the image to standout.Researchers have measured the quantitative relationship between arc light intensity and arc length, and have controlled arc length by arc light intensity sensing [5-6]. In general, arc light intensity can be transformed into voltage by a photo electric element. The relationship between voltage signal and arc light intensity is as follows

$$V = \int_{\Delta\lambda} R(\lambda)\varphi(\lambda)\,d\lambda \tag{1}$$

where V is the voltage, $\Delta\lambda$ is the corresponding spectral band of the photo electric element, $R(\lambda)$ is the photo electric element's response to radiant flux, $\varphi(\lambda)$ is the arc light spectrum radiant flux accepted by the photoelectric element.

Further research shows that the quantitative relationship between the arc light intensity and arc length is

$$V = M_1 IL + M_2 L + M_3 \tag{2}$$

where V is the arc light intensity [V]; I is the welding current [A]; L is the arc length [mm]; $M_1$, $M_2$, $M_3$ are constants. In the manual arc welding, $M_1$ =0.01033, $M_2$ =-0.4834, and $M_3$ =0.16514.

Therefore, the radiant intensity of the arc light spectrum can be calculated from the arc length and welding current using Eqs.1 and 2.The welding arc is a solid light source, every part of which radiates arc light, and the arc covers the arc welding area like a bell. Figure 1 shows the shape of arc. Because the radiant arc light is anisotropic, the shape, vertex angle and abrasion of the tungsten electrode, as well as the current and the arc length, play an important role in the weld pool image during the welding process. When the welding current decreases, the central area of the arc gradually decreases and shrinks to a point. At this time, the welding arc can be regard as a point illumination, as the relation is the same in all directions.

Therefore, the arc light intensity of a point source per unit solid angle is

$$I_0 = \frac{\varphi(\lambda)}{4\pi} \tag{3}$$

The relationship between the gray level of the image of the object surface and the incident light intensity on the object surface can be formulated as

$$E(X,Y) = kR(x,y,z)I_2(x,y,z) \tag{4}$$

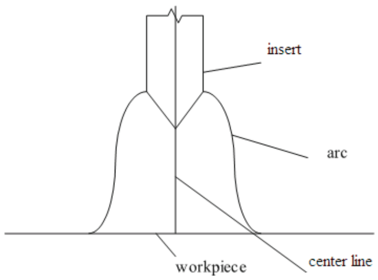


Fig.1 The arc shape

where E(X,Y) is image gray level at image point (X,Y), k is a constant relative to the camera, R*(x,y,z)* is the surface reflectance coefficient of the point $(x,y,z)$, and $I_2(x,y,z)$ is the light intensity of the object surface at the point $(x,y,z)$.

Knowing exactly the incident light intensity and the effect of light intensity on the equipment are important for weld pool imaging and for recovering the weld pool surface height from the weld pool image.

### 3. The structure of the visual sensing system

Weld penetration is an important characteristic of the weld quality. During the welding process, an experienced welder can visually acquire characteristic information from the shape of the weld pool, the metal transfer, and the arc behaviour, and adjust the corresponding welding parameters to ensure the required weld penetration. There is abundant information about the welding status in the visual information from the topside shape of the weld pool. Therefore, the visual sensing of the topside of the weld pool can be used to observe the welding quality and to control the welding parameters to ensure the required welding quality. Figure 2 shows a diagram of the topside visual sensing of the weld pool.

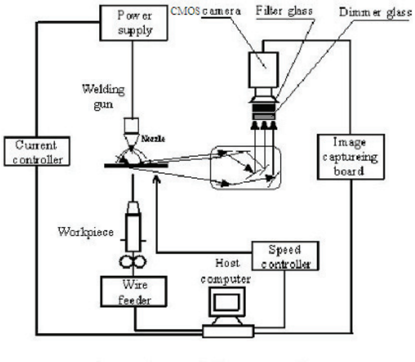


Fig.2 Schematic diagram of visual sensing of the weld pool

Because the operation of the camera is influenced by environmental factors such as temperature changes, electromagnetic disturbances, splatter and fumes, and nozzle occlusion during capturing the weld pool image, which reduce the top arc light input, the camera should be placed at a certain angle. To observe the seam, the weld pool, and the offset between the seam and the centre of weld pool in the same image, the camera should be placed in a suitable position.

The welding arc light reaches the camera through a piece of glass, a neutral-density filter, and a narrow-band filter, after reflection from the weld pool, the welding work piece, and the seam. The glass can prevent spatter and fumes from polluting the optical components as well as the camera lens.

### 4. The analysis of the sensing system

According to optical principles, the practical optical system is approximately linearly in variant and spatially in variant under the operating conditions. Thus, the camera imaging system, which is composed of a lens and CMOS camera, can be regarded as a linear system. Therefore, the light intensity reaching the camera can be processed as a combination of the light intensity from the object surface and the attenuation from the imaging system. In order to calculate the light intensity reaching the camera and to obtain the surface height of the weld pool from the weld pool image, it is necessary to analyze the imaging system and model it. The passive visual sensing system is moderated by a neutral-density filter, a narrow-band filter, and the adjustment of camera settings. These adjustments include a neutral-density filter, a narrow-band filter, focus adjustments, shuttle adjustments, and aperture adjustments.

### 4.1 Neutral-density filter adjustments

Because the arc light intensity is much greater than the receiving range of the CMOS camera, it is necessary to reduce the incident light intensity. A neutral-density filter can absorb light to fall wave lengths equally, so filters for different levels of transmission can be selected according to the required arc light attenuation. However, if only a neutral attenuation method is adopted, arc disturbance must still be suppressed, as the contrast and resolution of the weld pool image decreases and detailed information about the image is lost. Therefore, a narrow-band filter is used
to absorb the arc light selectively and to make the unclear detail clear.

### 4.2 Narrow-band filter adjustments

A narrow-band filter is a kind of interference filter that transmits monochromatic light and which makes use of a multi-beam optical interference principle. In the optical instrument, the interference filter is mainly used to eliminate excess light and to enhance the sensitivity of instrument.[7]

Figure3 shows the frequency-response curve of the narrow-band filter; the parameters include maximum transmission $\tau_{max}$, centre wavelength $\lambda_0$, half-width $\Delta\lambda_{0.5}$ , $\Delta\lambda_{0.1}$ when the transmission is $0.5\tau_{max}$ and $0.1\tau_{max}$, and the waveform coefficient $\eta=\lambda_{0.1}/\lambda_{0.5}$. These parameters can be obtained by testing the narrow-band filter. The frequency-response curve can be approximated according to the above parameters.

In this paper, a Gaussian function is used to describe the function of the narrow-band filter in the visual sensing system.

The formula of the Gaussian function is

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-a)^2}{2a^2}} \quad (5)$$

Therefore, the function of an arrow-band filter can be formulated as follows

$$W(\lambda) = \tau_{max} \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(\lambda-\lambda_0)^2}{2a^2}}, |\lambda - \lambda_0| \leq \Delta\lambda \quad (6)$$

### 4.3 Adjusting the narrow-band filter

In passive visual sensing, the continuous spectrum component of the arc light can be regarded as noise or background, in contrast with the peak spectrum. The narrow-band filter can be used to increase the signal-to-noise ratio of the weld pool image, to decrease the effect of the peak spectrum, to reduce the function of the metal component in the metal spectrum, and to utilize the arc light as the light source for acquiring a clear weld pool image. Because the spectrum response sensitivity range of the CMOS is 400–900nm while the arc light wave length range is 600–700nm for stainless steel [8], a suitable narrow-band filter can be chosen to selectively filter out undesired wavelengths.

### 4.4 Adjustments of the CMOS camera

The CMOS camera system includes an optical lens and a CMOS camera. In order to acquire a clear image of weld pool, the optical lens, the shuttle, the aperture, and the focus must be adjusted exactly. In general, the neutral-density filter can be used as a coarse adjustment of the light intensity, while the aperture serves as a fine adjustment. When the depth of field is narrow, however, the role of the aperture is limited. The shuttle can therefore be used to provide a fine adjustment of light intensity. The lens adjustment includes modifying aperture, depth of field, and focus. Aperture is mainly used to control light intensity, the variation of which has a significant effect on image quality. When the aperture is too small, the image is too dark. If the aperture is very large, the image is too bright, and contrast in colour is lost. The function of the aperture corresponds to that of neutral-density filter.

The neutral-density filter absorbs all wavelengths of light equally and reduces the radiant flux reaching the camera. The common specification of neutral-density filters is 1/4ND, 1/8ND, 1/16ND, and 1/32ND. The transmission of these filters is 25%, 12.5%, 6.25%, and 3.125%, respectively, corresponding to aperture level number decreasing by 2, 3, 4, and 5.

The shuttle can shorten the exposure time of the camera, corresponding to a reduction in flux through the lens. A shuttle level increases, corresponds and increase in the neutral-density filter transmission. Adjusting the neutral- density filter, shuttle, or aperture can be used to reduce the flux through the lens, but the effects are not entirely equivalent. The neutral-density filter can change the flux through the lens, while the shuttle can shorten the exposure time of the camera and increase the definition of moving image. The aperture can reduce the flux and increase the depth of field, as well as the definition of a moving image.

Many optical instruments are needed to image the object at different depths of field. In general, increasing the depth of field can increase the range in which the image is clear. However, in order to accentuate the main part of image, the depth of field can be reduced. Depth of field is controlled through adjustment of the focus and the aperture.Focusing involves moving a lens to focus an image. Changing the focus changes the depth of field of the camera.According to the above analysis, adjustments of the aperture and the shuttle correspond to different neutral-density filters.

Neutral-density filters only reduce the light flux, while adjustment of the depth of field and the focus rarely influences the light intensity. The light intensity after the visual sensing system can be formulated as

$$I_1(\lambda) = W(\lambda) \cdot I_0(\lambda) \cdot \tau \qquad (7)$$

Where $I_0$ is the light intensity into the sensing system after reflection from the object surface, $I_1(\lambda)$ is the light intensity reaching the camera target, $W(\lambda)$ is the function of the narrow-band filter, and $\tau$ is the transmission of neutral-density filter corresponding to the shuttle and the aperture.

## 5. Experiments

### *5.1 The experimental equipment of the arc welding*

Table1is a list of the equipment used in our experiments. Table 2 is a list of the welding parameters. The work piece material is 42CrMo. Fig.3 shows the full path of the light. Fig.4 is a photograph of the experimental equipment.

Table.1 The experimental equipment used

| Welding power source | Welding rod | Welding torch |
| --- | --- | --- |
| Invert Elecon 300P | CHE-507 | AW-33 |

Fig.3 Full path of the light sensing system

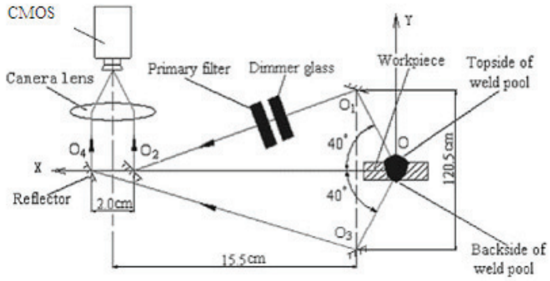


Table.2 The welding parameters used

| Pulse frequency(Hz) | Peak current(A) | Base current(A) | Arc length(mm) | Arc flow(l/min) | Workspiece size (mm×mm×mm) |
|---|---|---|---|---|---|
| 50 | 110 | 41 | 3 | 8.0 | 300×100×5 |

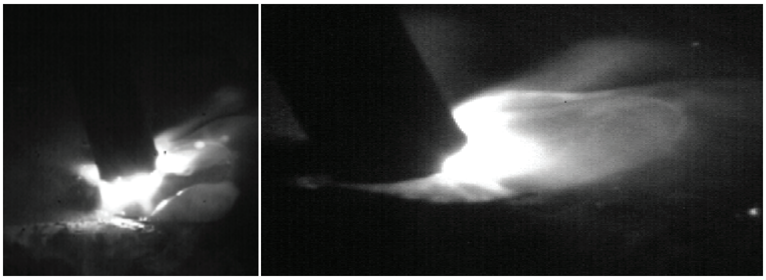

**Fig.4** Imagine of the weld pool

### *5.2 The visual sensing system*

Table.3 The parameters of the visual sensing system used

| Neutral-density filter | Narrow-band filter | Shutter | Focus | Apertus |
|---|---|---|---|---|
| 30%,50% | 808±10nm | 1/500 | 50mm | 16 |

The CMOS camera used is an MV-D1024E. Table 3 is a list of the parameters of the visual sensing system. Figure 5 shows an image of the weld pool. The parameters of the Gaussian function are as follows: $\tau_{max}$ is 0.33, $\lambda_0$ is 808nm, and σ is 3.

### *5.3 Discussion*

Because the arc light intensity and the adjustment system are quantified, the light intensity that reaches the camera is measured accurately. Then the gray level of the welding pool image describes the shape of the welding pool. We can obtain the shape of the welding pool from the gray shading more accurately compared to other equivalent systems.

## *6. Conclusions*

According to optical imaging principles, the characteristics of illumination are important for the imaging of an object. The variance of light intensity from an object surface will influence the gray level of the image. The principle of passive visual sensing was analyzed. According to welding principles, the light intensity of the welding arc can be calculated. The function of the complex filter system and the adjustments of the camera were analyzed. The function of the adjustments was described, and the relationship between the light intensity reaching the camera, the welding current, and the arc length was acquired. To allow comparison with other visual sensing systems, a quantitative analysis of arc light intensity was implemented and included consideration of the narrow-band filter, the neutral-density filter, the shuttle, the aperture, and the focus. We found that the gray level of the image can describe the shape of the welding pool accurately. The surface height and the shape of the weld pool can be calculated from the image of the weld pool by SFS algorithms.

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